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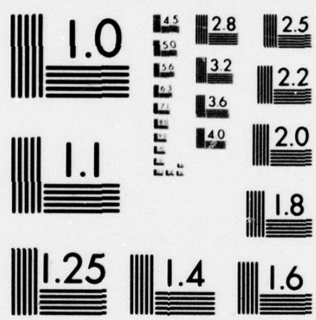

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RESPONSE OF MNOS DEVICES
TO NEUTRONS AND GAMMA RAYS

THESIS

AFIT/GNE/PH/78D-2 Steven J. Coloney
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RESPONSE OF MNOS DEVICES
TO NEUTRONS AND GAMMA RAYS.

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Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

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in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

by

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Graduate Nuclear Engineering

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Preface

This report is a continuation of the study by Ronald Fraass (Ref 3) into the use of Metal-Nitride-Oxide-Semiconductor transistors as radiation dosimeters for high dose levels. This research was sponsored by the Transient Radiation Effects Branch of the Air Force Weapons Laboratory (AFWL/ELT), Kirtland AFB, New Mexico.

I extend my gratitude to the Department of Energy (DOE) for funding the reactor operation through its Reactor Sharing Program.

I wish to thank Roger Tallon of AFWL for his role in procuring the MNOS transistors and the initial irradiation work.

Special thanks must be extended to Brian Hajek, Dr. Richard Bailey, and the staff of the Ohio State University Nuclear Reactor Laboratory for their assistance with the neutron irradiation of the MNOS transistors.

A debt of gratitude is also owed to my faculty advisors, Dr. George John and Dr. G. Richard Hagee, for their support and encouragement. Gratitude is also due to George Gergal for his work in designing and building the automatic circuitry used in this equipment.

Steven J. Coloney

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Abstract

Metal-Nitride-Oxide-Semiconductor (MNOS) transistors were evaluated as radiation dosimeters in the neutron-gamma radiation field of a nuclear reactor as compared to their behavior when exposed to gamma rays from a calibrated ^{60}Co source at 40.3 krads (Si) per hour.

Their response to gamma rays confirmed the results of a previous study (Ref 3) which showed that the change in the threshold voltage for conduction, ΔV_T, followed a relation $\Delta V_T = \Delta V_{TMAX} \cdot (1-e^{-BR})$ where R is the total absorbed dose and ΔV_{TMAX} is the maximum change in threshold voltage for an infinite radiation dose. For gamma irradiation, ΔV_{TMAX} approaches ≈ 5 volts at an exposure of ≈ 4 Mrads (Si). Response to reactor radiation follows the same relation except for an anomalous increase of $\approx 20\%$ in ΔV_{TMAX}. When shielded with cadmium, ΔV_T upon repeated irradiation is reproducible within 2% for four runs. When unshielded, a small parallel offset in ΔV_T results.

The devices have survived neutron fluences of 1.9×10^{16} cm^{-2}. After irradiation in the reactor, the responses of two devices to gamma rays were within 5% of pre-irradiation values.

A simple schematic is given for the testing circuit along with procedures to follow to determine gamma ray doses from the MNOS device.

RESPONSE OF MNOS DEVICES TO
NEUTRONS AND GAMMA RAYS

I. Introduction

The purpose of this study is to further evaluate the Metal-Nitride-Oxide-Semiconductor (MNOS) transistor as the detector in a radiation dosimeter, by exposing the transistor to high levels of neutrons and gamma rays. The MNOS transistor is a charge storing device. A radiation dose absorbed by the device will reduce the amount of that charge in a predictable way. The dosimeter uses, as a measure of the magnitude of the stored charge, the gate voltage that causes the transistor to conduct an amount of current over some threshold value. This threshold voltage will vary depending upon the amount and type of charge stored in the MNOS transistor.

The MNOS transistor has been shown to be an effective gamma ray dosimeter for high dose levels, from 10 krads (Si) to 4 Mrads (Si) (Ref 3). The study showed that they could repeatably measure doses with a precision of ± 2% (Ref 3:38). The transistors could be read directly while still in the radiation field and were electrically resettable after measuring an accumulated dose. They seemed to be unaffected by a total dose of 20 Mrads (Si) and appeared to be independent of dose rate.

Previous studies indicated MNOS transistors suffered no ill effects from being exposed to neutrons from a fast burst nuclear reactor (Ref 9). A brief report by Girii, et al. indicates that MNOS transistors are relatively insensitive to neutrons from a critical reactor as compared with gamma rays.

Scope of the Study

The MNOS transistors of this study were to be irradiated in a calibrated ^{60}Co gamma ray source and in a critical nuclear reactor. It was planned that the response of the transistors to calibrated gamma ray doses could be determined before and after irradiation in the reactor to serve as a measure of neutron radiation damage. The response of the transistor to the mixed gamma ray and neutron radiation of the reactor could give general information on the relative sensitivity of the MNOS to neutrons in a high gamma ray flux. Covering the MNOS transistors with cadmium would disclose effects due to thermal neutrons versus fast neutrons.

It was recognized that in using a reactor for a source of neutrons, the investigator would be unable to isolate the effects of neutrons and gamma rays. A neutron generator was preferred but unavailable for this study.

The investigation was limited to the study of a group of 5 MNOS transistors. The data obtained provided input to the applicability of MNOS devices as neutron dosimeters and to the effects of

neutrons.

Approach

Chapter II gives the theory of operation of MNOS transistors and the theory behind their use as a radiation dosimeter. A description of the transistors, the experimental setup, the procedures used, and the experiments done on the transistors are described in Chapter III. The results of the experiments are presented in Chapter IV, with Chapter V containing a discussion of the significance of the results and some recommendations for further research.

II. MNOS Theory

The Metal-Nitride-Oxide-Semiconductor (MNOS) transistor was developed with the hope of producing a better Metal-Oxide-Semiconductor-Field-Effect-Transistor (MOSFET). An MNOS transistor would have two layers of insulator and therefore, a higher input resistance than the MOS transistors. When the first MNOS transistors were tested to determine their electrical characteristics, their threshold voltages were found to be variable. This newly discovered hysteresis effect led to their use in memory arrays. Radiation hardness testing of these memory arrays spawned the idea of using the MNOS transistor as a radiation dosimeter. Fraass' study (Ref 3) has shown that the MNOS transistor responds repeatedly to gamma ray doses with a high degree of precision. This chapter describes the MNOS structure, its operation, the theory of its operation, changes in the threshold voltage due to time and radiation and the read-disturb effect, i.e. disturbance created by reading the threshold voltage.

MNOS Structure

The MNOS transistor is a member of the insulated-gate-field-effect-transistor family. A typical MNOS transistor is shown in Fig. 1; the ones used in this experiment are similar to it. Figure 1

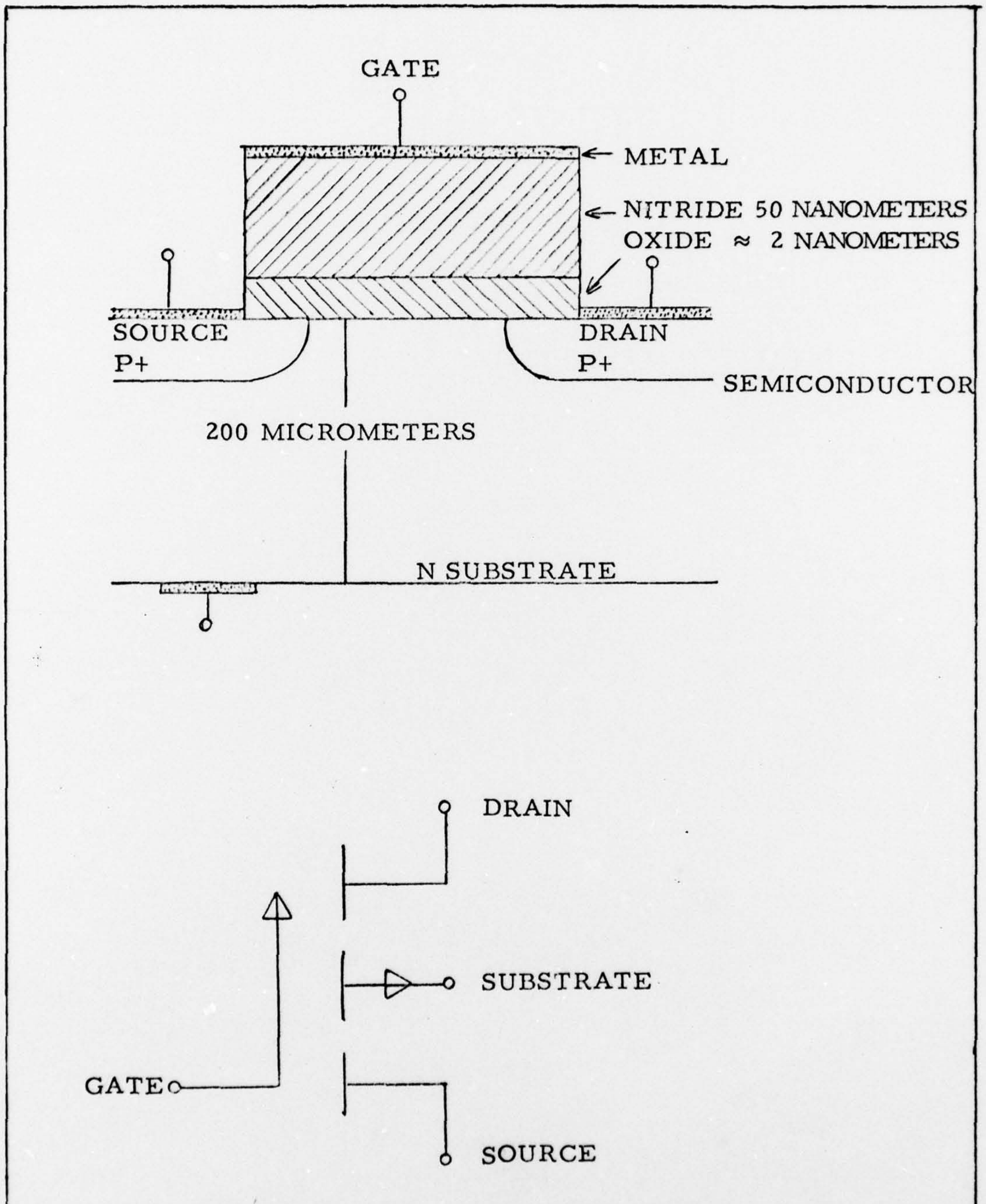

Fig. 1. P-Channel Enhancement Mode MNOS Transistor and Symbol (Ref 3:6)

shows a p-channel enhancement mode transistor consisting of a substrate of 200 micrometers of lightly doped n-type silicon with source and drain regions of heavily doped p-type material, and a gate region which lies between and above the source and drain regions. The gate contains a 2 nanometer layer of silicon dioxide (SiO_2) and a 50 nanometer layer of silicon nitride (Si_3N_4). Aluminum contacts provice electrical connection to the transistor.

MNOS Operation

Operation of the p-channel enhancement mode transistor depends upon the voltage applied between the gate and substrate (V_{GS}). When V_{GS} is a negative voltage of sufficient magnitude, a current will flow between source and drain (I_{SD}). This negative V_{GS} causes holes to be drawn up to the substrate-oxide interface, thereby providing a positive conduction channel for current to flow.

Threshold Voltage. Threshold voltage (V_T) is defined as the value of V_{GS} needed to cause a small amount of current to flow between source and drain. In this study, V_T was arbitrarily defined as that voltage needed to cause the total I_{SD} to be 9.55 microamps above the leakage current. The value of the variable threshold voltage depends upon the conduction state of the transistor.

Conduction State. An MNOS device can operate anywhere between two extreme states of conduction described as high saturated

and low saturated. A high-conduction state occurs when electrons are trapped in the nitride, while a low-conduction state results when holes are trapped. Fig. 2 shows a set of curves featuring V_{GS} vs I_{SD} for a typical device. The two outside lines show the saturated high and the saturated low conduction states. The actual V_{GS} vs I_{SD} curve can range anywhere between the upper and lower limits. The threshold voltage V_T is shown for both states along with the leakage currents. The center curve, marked stable, shows V_{GS} vs I_{SD} for a transistor that has no charges trapped in the nitride layer. The magnitude of the V_T will always range between the high and the low curves with typical values between -0.5 volts to -12 volts, respectively. The threshold voltage indicated by V_{TO} can be called the stable threshold voltage. It does not change with time.

Writing. Writing is the process by which the transistor is placed into either conduction state. This study defined writing as placing the transistor in the high conduction state. It is the act of storing negative electrical charges in the silicon nitride layer of the transistor. This can be accomplished by applying a large positive V_{GS} pulse for a sufficiently long time. In this study a +24 volt - 1 second long V_{GS} pulse was used as a write pulse. The large positive signal on the gate causes electrons to quantum-mechanically tunnel through the oxide layer to reach the nitride layer and the gate. Some of these electrons enter into deep traps in the nitride. When the

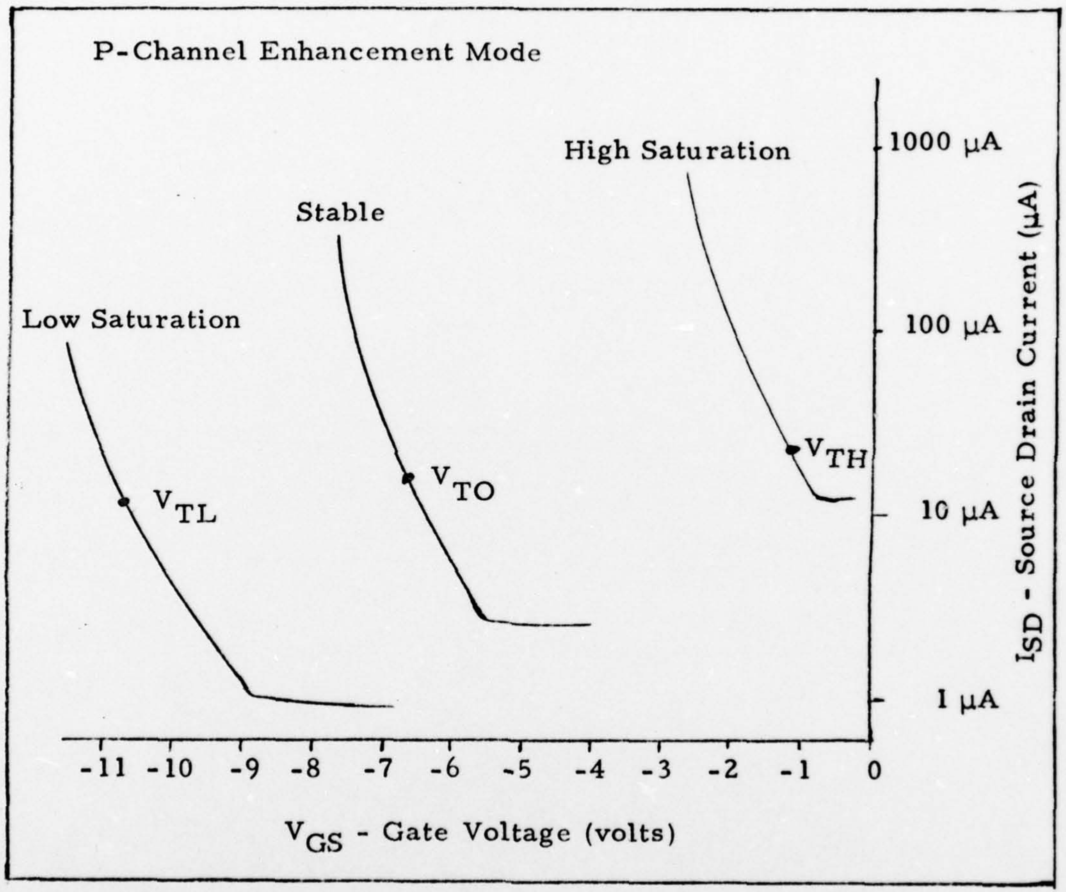

Fig. 2. Generalized Curves for Source Drain Current (I_{SD}) Versus Gate Voltage (V_{GS}) (Ref 3:8)

number of electrons reaching the gate equals the number tunnelling through the oxide, saturation has occurred. After the write pulse has stopped, these trapped electrons pull holes up to the oxide-silicon interface to form a partial conduction channel from source to drain. The magnitude of the threshold voltage is lowered and the amount of leakage current increases.

Clearing. Clearing is defined as the process by which the transistor is placed in the low conduction state. The clear pulse is a large negative V_{GS} pulse that causes positive electrical charges to be stored in the nitride layer. A pulse of -24 volt with 1 second duration was used as a clear pulse in these studies. The large negative signal on the gate causes holes to tunnel through the oxide layer into deep traps in the nitride layer. Saturation occurs when the number of holes leaving the nitride through the gate equals the number tunnelling through the oxide. At the end of the clear pulse, the trapped positive charges pull electrons up to the oxide-silicon interface to block the conduction channel. These electrons cause the magnitude of V_T to be much higher and reduces the leakage current.

Mechanism of Operation

A more detailed explanation of the theories behind the movement of charges in MNOS transistors can be found in articles by Frohman-Bentchkowsky and Lenzlinger (Ref 4), Svensson and Lundström (Ref 8)

and most recently by Chang (Ref 2). Chang models the movement of charges from the silicon substrate to the nitride layer by several processes (Ref 2:512-513). Two of the processes involve high energy electrons or holes that are not normally found under practical operating conditions. The other two processes occur while the transistor is being subjected to a write or clear pulse.

If the transistor is initially uncharged and is being subjected to a write (positive) pulse, at the gate, the energy band-level diagram will look like Fig. 3. As a consequence, electrons tunnel from the silicon conduction band through the oxide potential energy barrier to the nitride conduction band. When the charges get into the conduction band, they will either fall into local traps or will drift further into the nitride layer, where they are thought to be trapped according to the trapping model put forth by Arnett and Yun (Ref 1). This direct band-to-band tunnelling will dominate over the following process in the initial stages of the write pulse.

As the number of charges in the nitride layer build up, the potential energy band diagram changes to look like Fig. 4. Electrons now have to tunnel through the oxide potential energy barrier and part of the nitride potential energy barrier. This process is called the modified-Fowler-Nordheim tunnelling by Svensson and Ludström (Ref 8). Toward the end of the write pulse the tunnelling process becomes dominated by this second process.

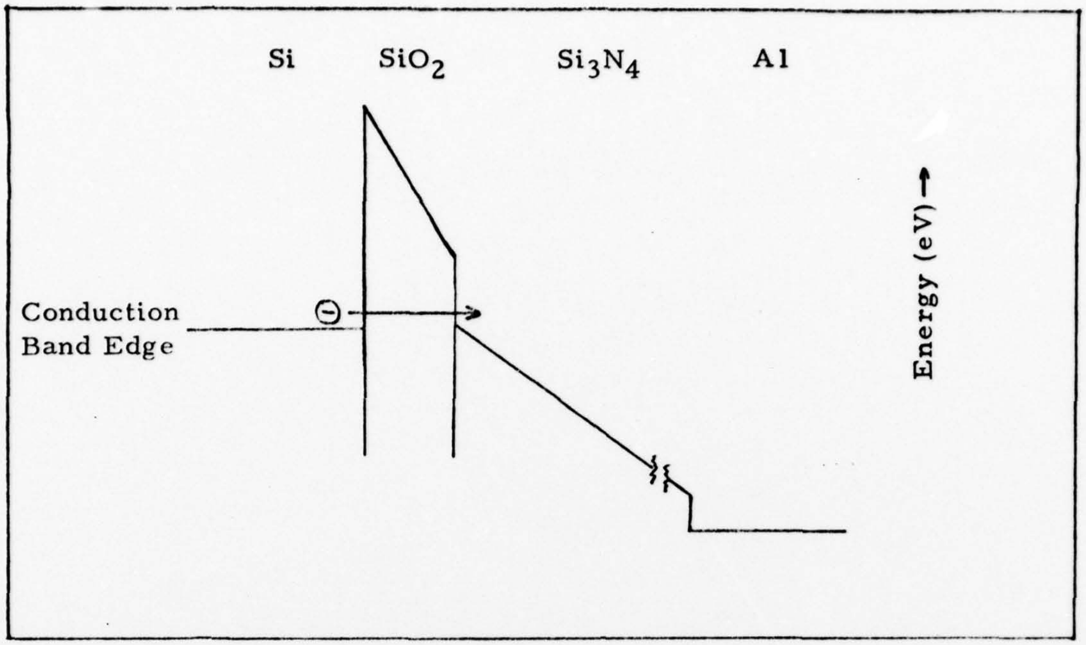

Fig. 3. Energy Band Diagram - Direct Band-to-Band Tunnelling (Ref 2:512)

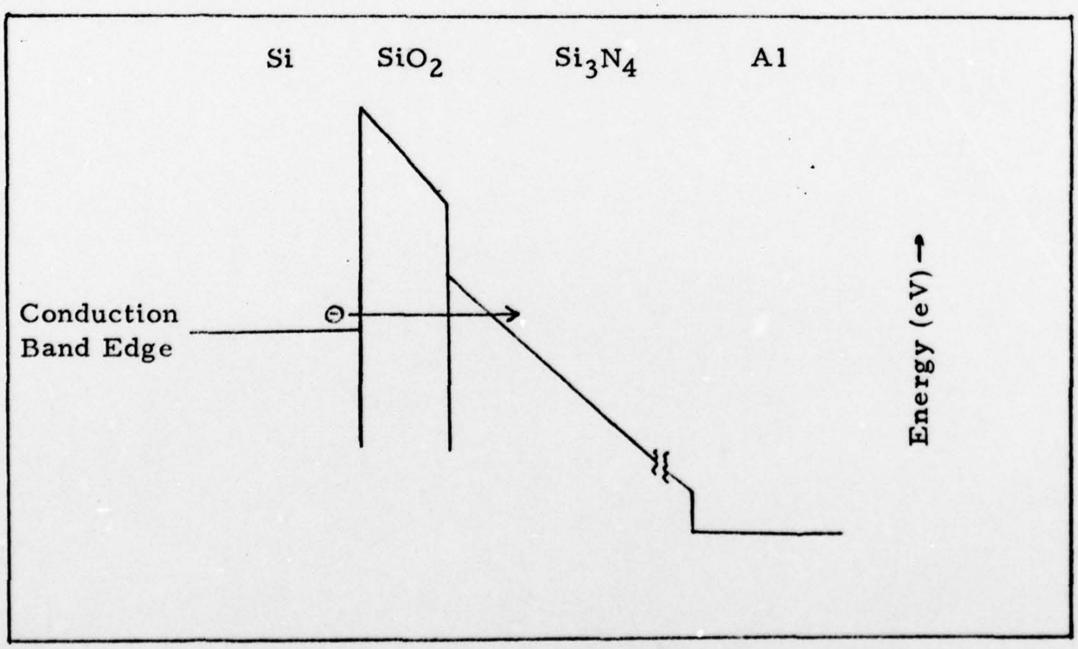

Fig. 4. Energy Band Diagram - Modified Fowler-Nordheim Tunnelling (Ref 2:512)

As more charges build up in the nitride layer, some of the electrons near the metal gate are detrapped and escape. Also, there is a reduction in the number of charges tunnelling through the oxide potential energy barrier. When the number of electrons detrapping at the gate equals the number of electrons tunnelling through the potential energy barriers, saturation has been reached. The total number of trapped charges depend on the device and the voltage of the write or clear pulse.

Changes with Time

After the write pulse, the gate voltage is returned to zero. The trapped electrons start to tunnel back to the silicon due to their induced electric field. This reverse tunnelling decreases the amount of stored charge in the nitride layer, thereby causing an increase in the magnitude of the threshold voltage. The change is linear in log time as seen in Fig. 5 and in the article by White and Cricchi (Ref 11:1286). This charge removal process is also the mechanism responsible for changes in the threshold voltage due to the absorbed radiation dose.

Radiation Effects

Radiation causes shifts in the threshold voltage of MNOS transistors by the production of electron hole pairs in the nitride layers. The interaction of gamma rays can produce Compton and

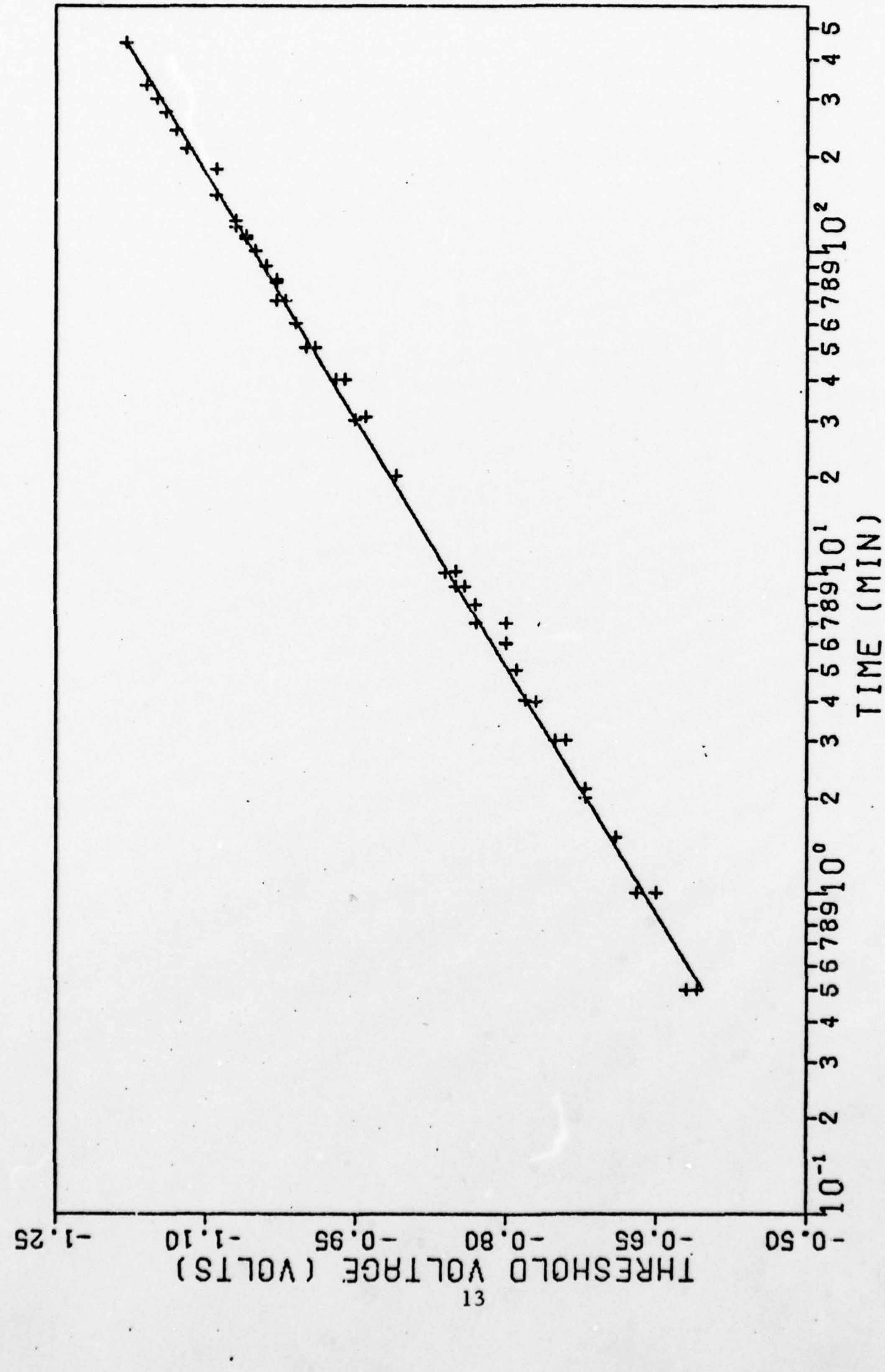

Fig. 5. MNOS Threshold Voltage Versus Time, Device #17

photo-electrons which then produce these electron hole pairs. As these radiation-induced charges slow down and lose energy, they drift in the internal electric field caused by the trapped charges, and thus cause the conductivity of the nitride layer to increase which allows the stored charge to leak out. As a consequence, the reduced charge in the nitride layer causes an increase in the magnitude of the threshold voltage.

Theory. The empirical equation relating the shift in threshold voltage in an MNOS transistor to the accumulated radiation dose was proposed by Wegener et al. (Ref 10). It is based upon the applied electric field, the space charge, and current in an insulator. The flow of radiation-induced changes is modeled by ohmic transport of the induced space charge in the insulator. Wegener et al. assumed that the trapped charge is stored at the oxide-nitride interface. A modification of this model by Williams and Nichols (Ref 12) assumes the trapped charge is stored throughout the nitride layer. A portion of the Wegener et al. model with the modification is presented here.

The gate of the MNOS transistor is approximated as a two-layer insulator as shown in Fig. 6. The trapped charge in the nitride is modeled by a sheet of charge per unit area σ located a distance of X_1 from the silicon and X_2 from the gate. A study has shown (Ref 6) that the very thin oxide layer is incorporated into the nitride layer during deposition, which alters the properties of this part of the

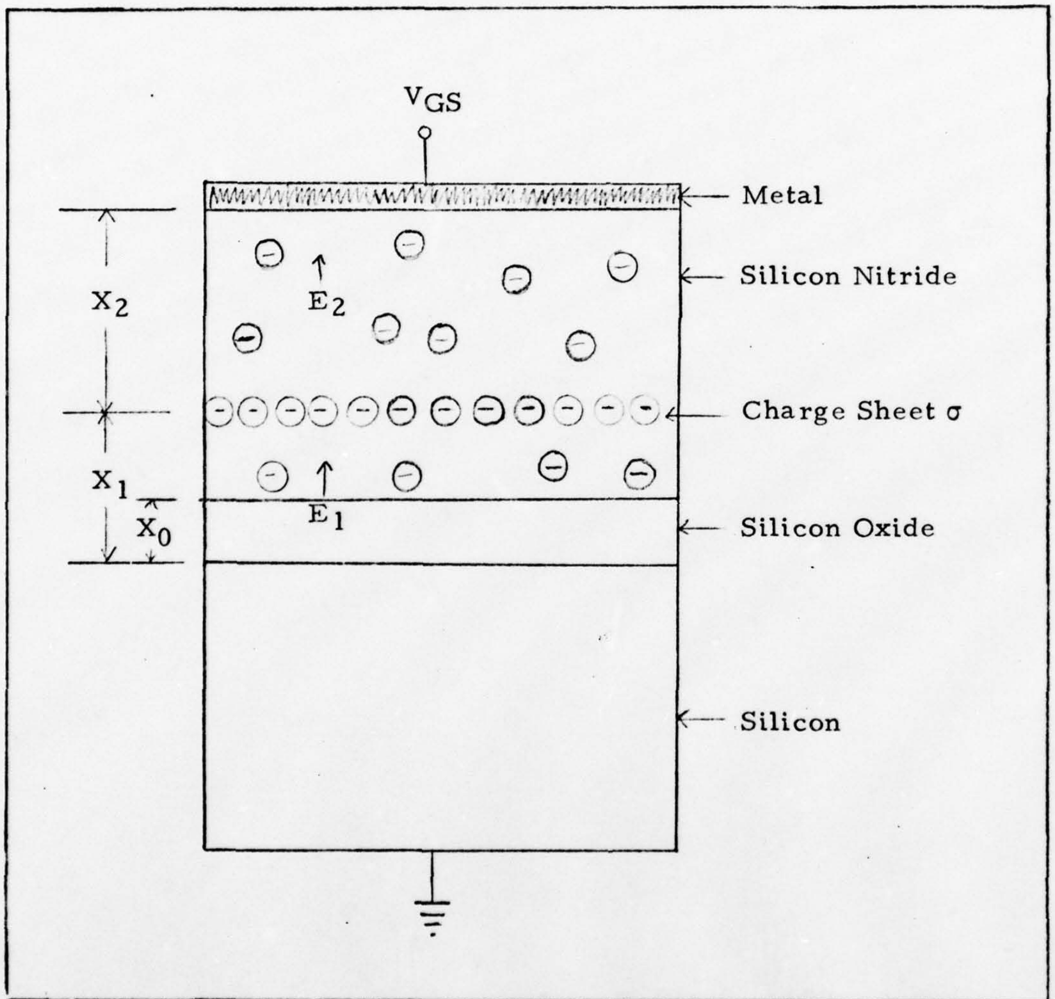

Fig. 6. MNOS Gate Region (Ref 3:14)

nitride layer. This situation is approximated by assuming that the thickness X_1 is silicon nitride, with a slightly different dielectric constant ϵ'_N than the silicon nitride in the X_2 region.

When no voltage drop within the silicon is assumed, the following relationship holds for the applied voltage V_{GS} and the charge per unit area, σ

$$E_2X_2 + E_1X_1 = V_{GS} \tag{1}$$

$$\epsilon'_N E_1 - \epsilon_N E_2 = \sigma \tag{2}$$

where ϵ'_N and ϵ_N are the dielectric permativities, and E_1 and E_2 are the electric fields for the nitride regions X_1 and X_2, respectively.

It is assumed that the value of σ is responsible for changes in the flatband voltage, V_{FB} where V_{FB} is defined as that value of V_{GS} that gives $E_1 = 0$. This relationship, when combined with equations (1) and (2), gives

$$V_{FB} = -\sigma \frac{X_2}{\epsilon_N} \tag{3}$$

Solving equations (1), (2), and (3) for E_1 and E_2, one results in

$$E_1 = \gamma\epsilon_N(V_{GS} - V_{FB}) \tag{4}$$

$$E_2 = \gamma\epsilon'_N(V_{GS} + \beta V_{FB}) \tag{5}$$

where $\gamma = (\epsilon_N X_1 + \epsilon'_N X_2)^{-1}$ and $\beta = \epsilon_N X_1/\epsilon'_N X_2$.

Equations (4) and (5) are valid for E_1 and E_2 at any time. To find V_{FB} as a function of time, the current continuity equation is used.

$$\epsilon'_N \frac{dE_1}{dt} + J_1 = \epsilon_N \frac{dE_2}{dt} + J_2 \tag{6}$$

where J_1 and J_2 are the current densities in A/cm^2 for the two regions. Equation (6), when rearranged and integrated gives an explicit equation for the time required for V_{FB} to change from V^i_{FB} to V^f_{FB}.

$$t = \int_{V^i_{FB}}^{V^f_{FB}} \frac{\epsilon'_N dE_1 - \epsilon_N dE_2}{J_2 - J_1} \tag{7}$$

By differentiating equation (2), combining it with equation (3) and substituting them into equation (7), one finds that time becomes a function of V_{FB}.

$$t = \frac{\epsilon_N}{X_2} \int_{V^i_{FB}}^{V^f_{FB}} \frac{-dV_{FB}}{J_2 - J_1} \tag{8}$$

Equation (8) holds for any two layer insulator system on a non-degenerate semiconductor. After the denominator is changed to $J_2 + J_1$, equation (8) gives the amount of time it takes to change from

the initial V_{FB} to the final V_{FB} by removing charges from the nitride layer. By using the proper functions for J_2 and J_1 and the proper limits, one can find the flatband voltage as a function of time by integrating equation (8).

The response to radiation is included by use of radiation-induced current densities J_{1R} and J_{2R}. In the modification of the Wegener et al. model by Williams and Nichols, they assume the radiation-induced charges are trapped in the nitride layer before they reach thermal equilibrium. It is their drifting during the slowing down process that makes up an ohmic conduction current in the nitride layer. Williams and Nichols (Ref 12:1554) proposed that the radiation-induced current conductivity K_N is defined in the two regions by

$$J_{1R} = K_N E_1 \dot{R} \tag{9}$$

$$J_{2R} = K_N E_2 \dot{R} \tag{10}$$

where, J_{iR} is the radiation-induced current density and $\dot{R}$ is the ionizing radiation dose rate in rads/second. The epithermal conduction model of J_R is explained in much greater detail in the Williams and Nichols article (Ref 12:1555-1557).

By substituting equations (4) and (5) for E_1 and E_2 into the equations for J_{1R} and J_{2R}, one results with the following two

equations.

$$J_{1R} = K_N \dot{R} \gamma \epsilon_N (V_{GS} - V_{FB}) \tag{11}$$

$$J_{2R} = K_N \dot{R} \gamma \epsilon'_N (V_{GS} + \beta V_{FB}) \tag{12}$$

Equations (11) and (12) are substituted in equation (8), leading to

$$-BR = \int_{V_{FB}^i}^{V_{FB}^f} \frac{dV_{FB}}{AV_{GS} + V_{FB}} \tag{13}$$

where:

$$B = K_N (X_1 + X_2) / \epsilon_N X_1 + \epsilon'_N X_2) \tag{14}$$

$$R = \dot{R}t, \text{ the absorbed dose} \tag{15}$$

$$A = (\epsilon'_N / \epsilon_N - 1)/(1 - X_1/X_2) \tag{16}$$

Upon integration and rearrangement, equation (13) leads to

$$V_{FB} = V_{FB}^i \exp(-BR) + AV_{GS} \left| \exp(-BR) - 1 \right| \tag{17}$$

Equation (17) predicts that the flatband voltage is a function of an exponential decay of stored charge from the first term and an exponential accumulation of new charge from the second term.

By using the following relationship between flatband voltage, threshold voltage, and the stable threshold voltage

$$V_{FB} = V_T - V_{TO} \tag{18}$$

One can write equation (17) as

$$V_T = V_{TO}+(V_T^i - V_{TO})\exp(-BR)+AV_{GS}\left|\exp(-BR)-1\right| \qquad (19)$$

When the MNOS devices were exposed to radiation, the gate was grounded to the substrate except when V_T was being measured. Thus V_{GS} can be set to zero. Also the threshold voltage V_T, the stable threshold voltage V_{TO}, and V_T^i are replaced by ΔV_T, ΔV_{TMAX}, and O, respectively. These changes lead to

$$\Delta V_T = \Delta V_{TMAX}[1 - \exp(-BR)] \qquad (20)$$

where the magnitude of ΔV_T represents the change in threshold for a given radiation dose R. The value for ΔV_{TMAX} represents the maximum threshold voltage shift for an infinite radiation dose. Equation (20) has been shown to fit the experimental data for an MNOS transistor being irradiated with Cobalt-60 gamma rays with a 2% precision (Ref 3:35-37).

Read-Disturb

Reading is the process of applying a voltage to the gate of the MNOS transistor to determine the threshold voltage for conduction. The basis of the read-disturb effect can be seen in equation (19). Any V_{GS} signal will change the amount of stored charge in the nitride layer and thereby change the V_T. For this reason the read pulses must be kept much shorter than the pulses used to store charge in the nitride. A possible mechanism for this low field strength tunnelling is the trap-assisted charge injection model put forth by Svensson and Ludström (Ref 8).

III. Equipment and Procedures

This chapter describes the MNOS transistor, its holder and testing circuitry, the radiation facilities used, the standardized testing procedure used, and the individual experiments. Due to restrictions on proprietary information, minimal information is given on the exact structure or manufacturing techniques used to make the MNOS transistors in this experiment.

MNOS Transistor

The MNOS transistors used in this experiment are research and development devices. They are a small part of a much larger test circuit contained on a silicon chip. These chips were packaged in 14 pin, gold-plated flat packs. Only one MNOS transistor was used per flat pack, so only four pins were actually used, the gate, drain, source, and substrate. The other pins were connected to other unused parts of the test circuit. The gate and the source pins were also connected to two other unused transistors that have stepped gates, which have been shown to suffer irreparable radiation damage (Ref 3:39).

Standard MNOS production techniques were used to make the transistors used in this experiment. The dimensions shown in

Fig. 1 are typical of this type of thin-oxide memory transistors. These transistors were manufactured by Sandia Laboratories, Albuquerque, New Mexico, in May 1978. Because these devices were test transistors, they were built without diode protection for the gates. Any static electricity discharge into the gate could easily burn through the thin layers of insulator in the gate, destroying the transistor. Therefore special handling techniques were used to prevent any of the 14 pins from becoming ungrounded during transfers of the device from one holder to another.

Transistor Holder

The transistor was held in a 14-pin flat-pack socket called a Barnes Connector. Electrical connection was provided to the Barnes Connector in two different ways. In the first holder, the Barnes Connector was mounted on a 15-contact plug board measuring 3-1/2 inch by 2-1/2 inch. A 2 inch by 7 inch square aluminum box with a 15 socket circuit board holder was used to hold the plug board during gamma ray irradiation. Another circuit board holder with its sockets shorted together was used when the plug board was not in the aluminum box.

The second type of flat pack holder was designed for use in the nuclear reactor. It consisted of a Barnes Connector mounted on a 1 inch by 4-1/2 inch PC board. Three 19-foot RG174 coaxial cables

were connected to the gate, drain, and source pins on the back of the Barnes Connector. The rest of the pins were shorted together and connected to the source lead. The three cables end in BNC tees, enabling them to be connected to the automatic circuit while a grounding cap was still on the lead. Cellophane tape was used to hold the cables to the PC board.

Automatic Circuitry

The conceptual model for a simple, automatic, threshold-voltage determining circuit was put forth by Fraass (Ref 3:45). The circuit design and construction was accomplished by George Gergal, an AFIT electronics design technician.

Design. The circuitry consists of three separate parts designated read, write, and clear. The clear circuit consists of a 1 second long monopulse generator that turns on and then off, a transistor connected between -24 volts and the gate of the MNOS. The write circuit is the same except the voltage is +24 volts.

The read circuit is shown, slightly simplified, in Fig. 7. It starts with a 1 second, +5 volt pulse, integrates it into a -5 volt ramp, doubles and inverts it, and then adds the ramp to a pulse train that is at +10 volts for 0.2 milliseconds and 0 volts for 0.8 milliseconds. A final inversion sends a 1 second 0 to -10 volt modulated ramp that is divided into 1000 steps (0.01 volts/step) to the gate of the

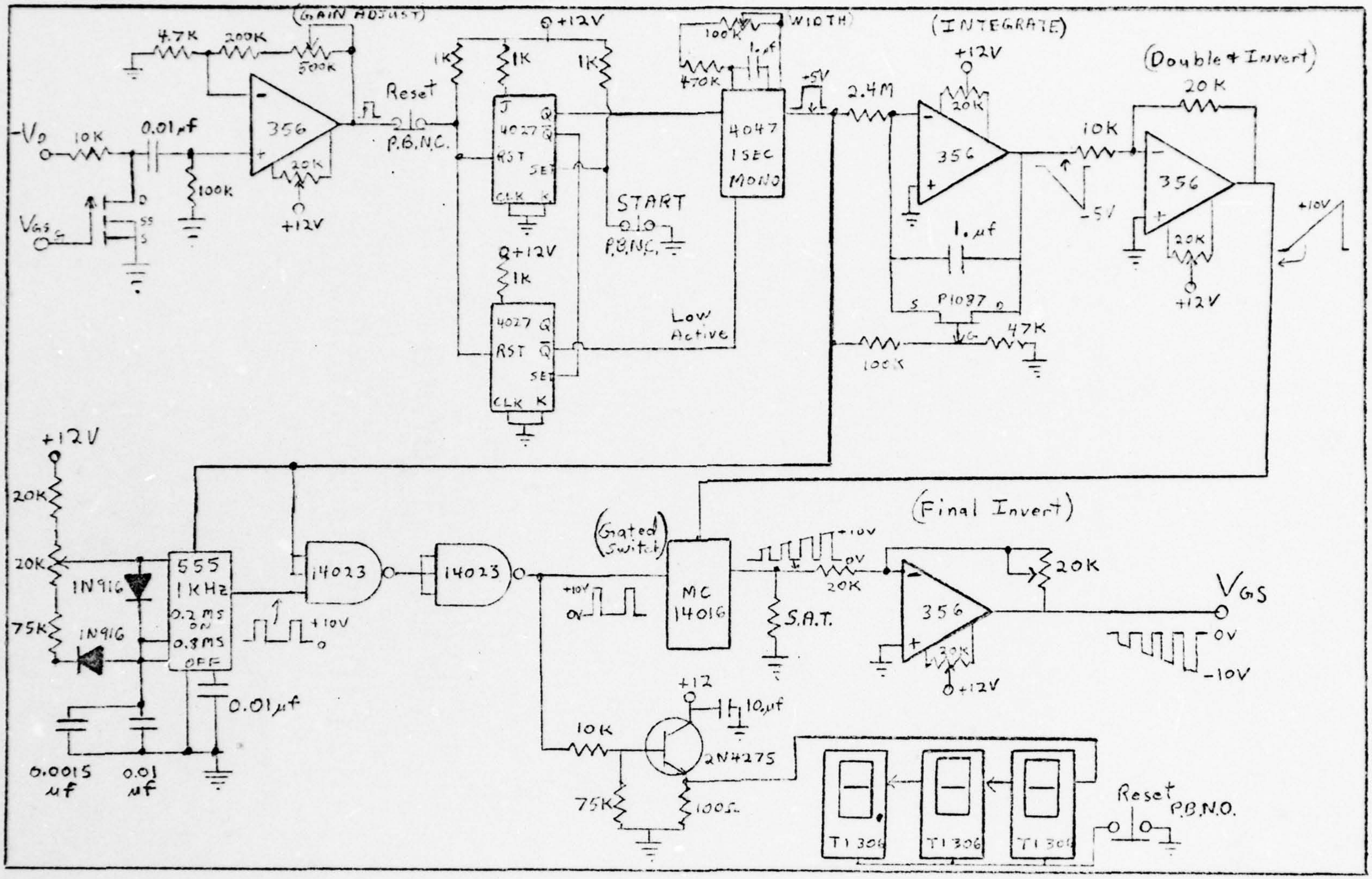

Fig. 7. Simplified Read Circuitry

MNOS. When the V_{GS} is large enough to cause the I_{SD} to reach the defined threshold current, the voltage drop across the drain resistor equals 0.1 volts. This 0.1 volt pulse, after amplification, triggers a flip-flop and also stops an array of digital counters that were counting each of the steps. The threshold voltage is then read off the counters in negative volts.

The automatic circuitry is contained in a 6 inch by 8 inch square box that also contains the five power supplies, switches and connectors, making the whole circuitry very portable.

Operation. Each of the circuits is actuated by a pushbutton switch. The read circuit has the added feature of a reset pushbutton to reset the flip-flops and the counters. This prevents an accidental erasure of the threshold voltage reading. A three-position rotary switch on the line leading to the gate of the MNOS prevents the feedback of a clear or write pulse into the last opamp in the read circuit.

Radiation Facilities

Three separate facilities were used to expose the MNOS transistors to ionizing radiation. Two facilities produce a gamma ray environment and the other is a combined neutron-gamma ray environment.

Gamma Facilities. The first facility used was the Air Force

Weapons Laboratory (AFWL) Gamma Irradiation Facility located at Kirtland Air Force Base, New Mexico. The facility uses Cobalt-60 gamma rays to give a maximum dose rate of 11.69 krads (Si) per minute at a distance of 6 cm from the source centerline.

The second Cobalt-60 source was the Gamma Irradiation Facility at the Air Force Institute of Technology (AFIT), Wright-Patterson Air Force Base, Ohio. The AFIT GIF is able to irradiate at sample at a dose rate of 40.3 kilorads (Si) per hour at the center of its source array. The gamma facilities were used to characterize the MNOS transistor's response to gamma rays both before and after testing in the nuclear reactor.

Reactor Facility. The reactor used was the Ohio State University Research Reactor (OSURR) located at Columbus, Ohio. It is a swimming pool type reactor using light water as a moderator. The reactor is fueled with uranium-aluminum alloy plates with the uranium enriched to 93% ^{235}U. Ten plates are arranged into a fuel element measuring 3 inch by 3 inch by 35 inch with 24 inch of active fuel length. Twenty of these fuel elements are arranged in a 5 X 5 matrix along with four control rods and the Central Irradiation Facility (CIF). The CIF is located in the center of matrix position (3, 3). It is a 1-1/2 inch diameter by 20 foot aluminum pipe that extends from the bottom of the core to above the surface of the water covering the reactor. It is a dry facility that allows access to the center of

the reactor core (Ref 7).

The MNOS transistors, mounted in the narrow holders, were irradiated in the CIF. The reactor was operating at a 10 kilowatt thermal power level for all of the experiments. The neutron flux was approximately 3.6×10^{11} neutrons/cm-sec, although it varied from device to device due to differences in absorption and local flux depression caused by the various device holders. The gamma flux was not known for the CIF, due to its small size, but a measurement at the edge of the core indicated an order of magnitude approximation to be between 10 to 80 krads per minute.

Standardized Testing Procedures

The time history of the MNOS transistor is very important because of the changes in threshold voltage V_T with time. Also important is the amount and polarity of the charge that is trapped in the nitride layer. To insure repeatable performance from a device, the above two factors have to be the same each time the device is tested.

Saturation of MNOS. A good point to start the history of a MNOS transistor is the point of saturation. This requires writing the device several times until the V_T changes by less than 0.01 volts. Care also has to be taken to insure that the write pulses are spread out in time to avoid putting a pseudo D.C. voltage across the gate,

risking permanent damage to the gate structure.

The method used in this experiment was to wait 10 seconds between write pulses. The number of write pulses needed to achieve saturation was determined by comparing the V_T's, measured 5 seconds and 30 seconds after the last write, as the total number of write pulses was increased.

The device can be rewritten while in the radiation field, which was done in these experiments to insure a constant flux of gammas and neutrons from the start of the time history.

Measurement of Neutron Flux. A copper wire was taped to the Barnes Connector to determine the neutron flux received by the transistor and holder. After a run in the reactor, the transistor and holder were pulled above the level of the core and were allowed to decay for 15 minutes or longer. The flux wire was then removed from the holder and allowed to decay further. The radiation from the flux wire was then analyzed with OSU Gamma Ray Spectroscopy System (a $Ge(L_i)$ detector and a Canberra Industries Multichannel Analyzer 8180) to determine the activity of the Copper-64 photopeak at 1.34 keV. A PDP 11/05 minicomputer program, developed at OSU, gives the activity of Copper-64 at the end of neutron irradiation from the data in the analyzer. By using the production rate formula for Copper-64, one can determine the neutron flux.

Experiments

The pattern of most experiments was to pre-test the MNOS device in the AFIT Gamma Irradiation Facility for 0.9 to 1.5 Mrads. Then the device was irradiated in the reactor for up to 12 hours. After the activated radioactive elements in the device and its holder had decayed to a reasonable level to permit transport, the transistors were returned to AFIT. Only two of the devices were able to be retested in the AFIT GIF; the others had been either accidentally shorted or not pretested.

Table I lists the device I.D. numbers and the experiments done with them. Device #17 was to have several OSURR runs, but was discovered to be electrically shorted out on the morning of the second day. Device #4 was substituted, without pretesting in AFIT GIF, for that day of runs. Device #15 was irradiated four times, separated by an overnight break between runs #2 and #3. It was post-tested. A cadmium cover was provided for Device #18 during its irradiation. There was a three day break between runs #2 and #3 for this device. The last device tested, #16, was run only once and then post-tested. Device #18 was the only cadmium covered device. Before each day of runs for Devices #18 and #16, the reactor was run at full power for approximately 1-1/2 hours in the hope of providing a more constant gamma flux by building up the inventory of short lived fission products in the core. Practically no change was observed when this was later analyzed.

Table I

Experiments Performed on Each Device

Device #	AFIT GIF Pre-test (Mrads)	OSURR Run #	Duration of Run (hrs)	Accumulated Neutron Fluence (cm^{-2})	AFIT GIF Post-test (Mrads)
17	0.95	1	3-1/3	$4.0X10^{15}$	----
4	none	1	3	unknown	----
		2	3	unknown	----
15	1.46	1	3-1/6	$5.0X10^{15}$	----
		2	2-5/6	$9.5X10^{15}$	----
		3	3	$1.4X10^{16}$	----
		4	3	$1.9X10^{16}$	5.70
18(Cd)	0.89	1	2-1/2	$3.3X10^{15}$	----
		2	1-1/2	$5.3X10^{15}$	----
		3	2-1/2	$8.6X10^{15}$	----
		4	1-1/2	$1.1X10^{16}$	----
16	1.29	1	3	$3.0X10^{15}$	3.97

IV. Results

The results section is divided into two parts. Data that was taken with the devices under gamma ray irradiation and that which was taken in the reactor.

Gamma Irradiation

The MNOS transistors were exposed to gamma rays in order to confirm the results that Fraass' study showed and to individually characterize the response of the MNOS devices to gamma ray doses. The initial screening of the MNOS transistors and the automatic circuitry was done at the AFWL Gamma Irradiation Facility. On return to AFIT, the transistors showed a change in characteristics. Retesting here showed the V_T of their saturation point was changed and the slope of the linear ln (t) time dependence was changed by as much as 17%. Therefore, each of the devices was retested in the AFIT Gamma Facility just before exposing them to the reactor irradiation.

Time Dependence. Fraass' work (Ref 3:12, 32) showed that the variation of V_T with time was linear on a logarithmic time scale. Fig. 5 shows two runs with the same device for 450 and 150 minutes plotted on a semi-log axes. A linear least squares fit to both sets of

data for V_T vs ln (time) yielded a correlation coefficient of 0.999. Fraass showed linearity for MNOS devices out to 47 hours. Because of this linearity, data for determination of changes in V_T with time was taken for only 30 to 60 minutes and extrapolated to later times.

Fig. 5 also shows that many data points are the same, indicating the kind of reproducibility of the data. Also apparent in Fig. 5 is how slowly the MNOS transistors in the study respond with time. This slow response is needed because of the long times required to accumulate a large total dose in the radiation facilities.

Radiation Dependence. Fig. 8 shows typical data taken at the AFIT gamma facility with the transistor reaching a total dose of 4 Mrads at the end of irradiation. It shows the combined effect of time and radiation on the threshold voltage. Also shown is the change in V_T due to time. Fig. 9 is the dosimetry calibration curve plotting the change in V_T due to the absorbed radiation dose. Equation (20) was fitted to these data by a nonlinear curve fitting computer program. The program found for this curve, a $\Delta V_{TMAX} = -4.791 \pm 0.014$ volts and a $B = 1.083 \pm 0.0090 \times 10^{-6}$ rad^{-1} with a minimum RMS error of 0.020. Because of time limitations, not all devices were calibrated to 4 Mrads. Data were taken up to 1 to 1.5 Mrads (Si) and then fit with equation (20). The values for B, the radiation damage constant, are all approximately 1.1×10^{-6} rads^{-1}, which agrees with the values quoted by Williams and Nichols (Ref 12:1554).

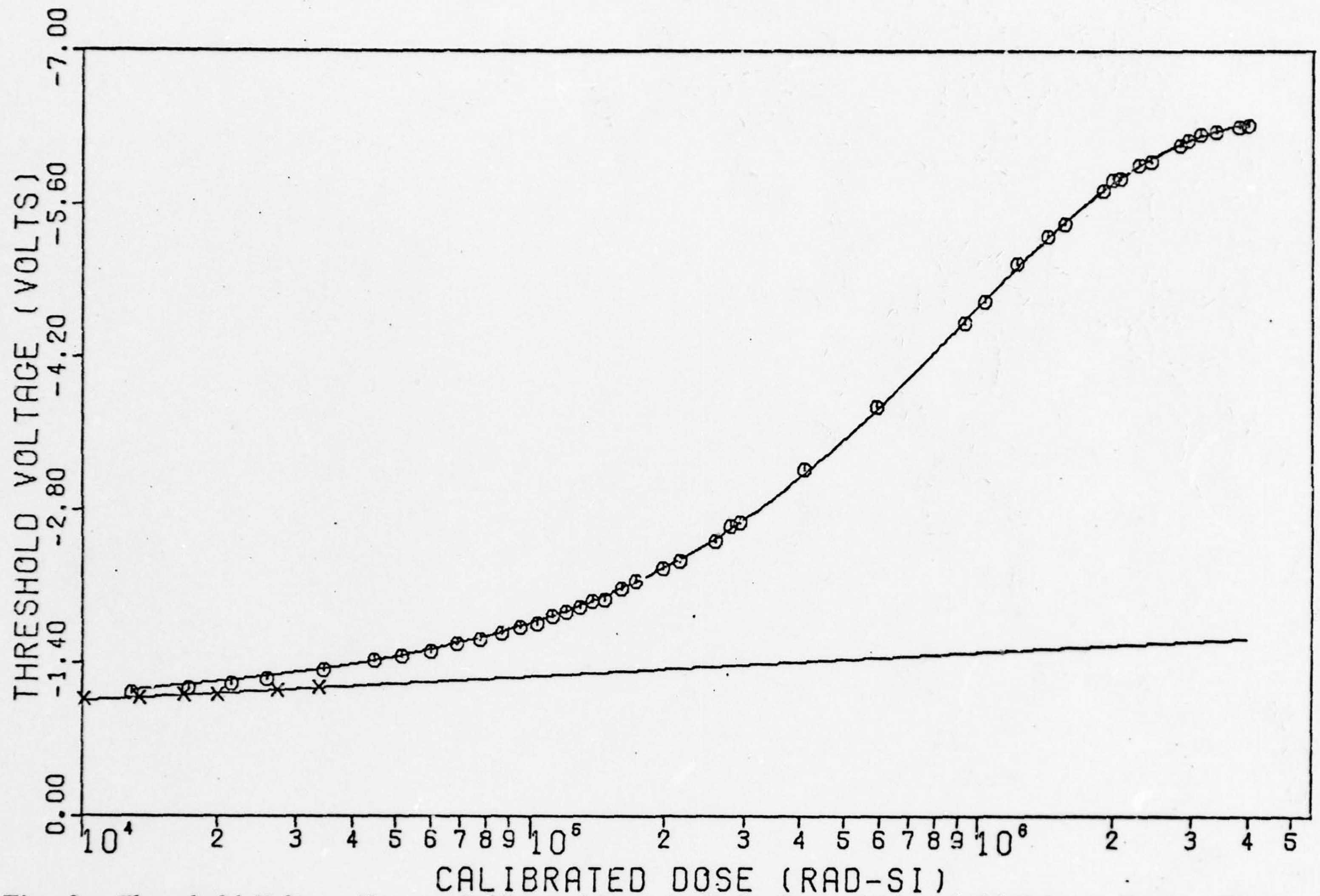

Fig. 8. Threshold Voltage Versus Calibrated Dose in Rads (Si) and Threshold Voltage Versus Time, Device #16

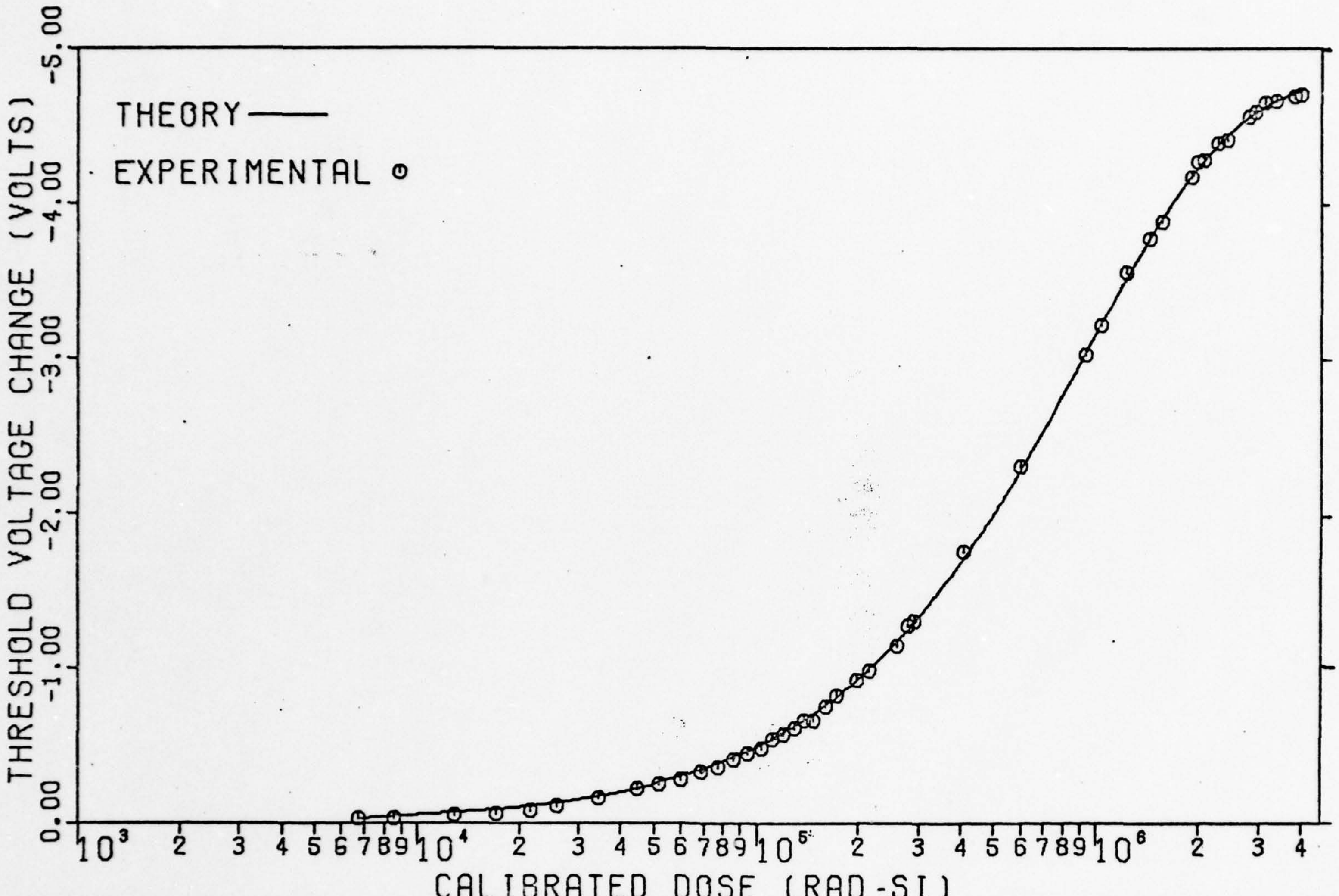

Fig. 9. Change in Threshold Voltage Versus Calibrated Dose in Rads (Si), Device #16

Reactor Irradiation

The MNOS devices were thought to be relatively insensitive to neutrons (Ref 5). This led to use of a nuclear reactor as a convenient source of neutrons. The MNOS device would respond to the gamma rays created in the fission process, with small effects being caused by the neutrons. Experimental data were then taken for changes in the threshold voltage due to time and radiation from the reactor.

General Response. The changes of threshold voltage with respect to time and neutron dose for a transistor in the radiation field of the reactor is shown in Fig. 10. Also plotted in Fig. 10 is the change of V_T due to time. This is the same device as seen in Figures 8 and 9. As can be seen, the ΔV_{TMAX} for this device in the reactor is larger than what was expected from the gamma ray data. A modification of equation (20) was made by changing the exponent of the exponential from BR to B'T where $B' = B\dot{R}$ and T is time. Equation (20) was then fitted to the data showing $\Delta V_{TMAX} = -5.66$ volts and $B' = 0.0396\ \text{min}^{-1}$ with an RMS error of 0.021. The anomalous increase in ΔV_{TMAX} prevented further comparisons between ΔV_{T}'s from the reactor and the gamma dosimetry calibration curve.

Repeatability. Two transistors were tested in multiple runs. The devices were rewritten to the high conduction state after the V_T

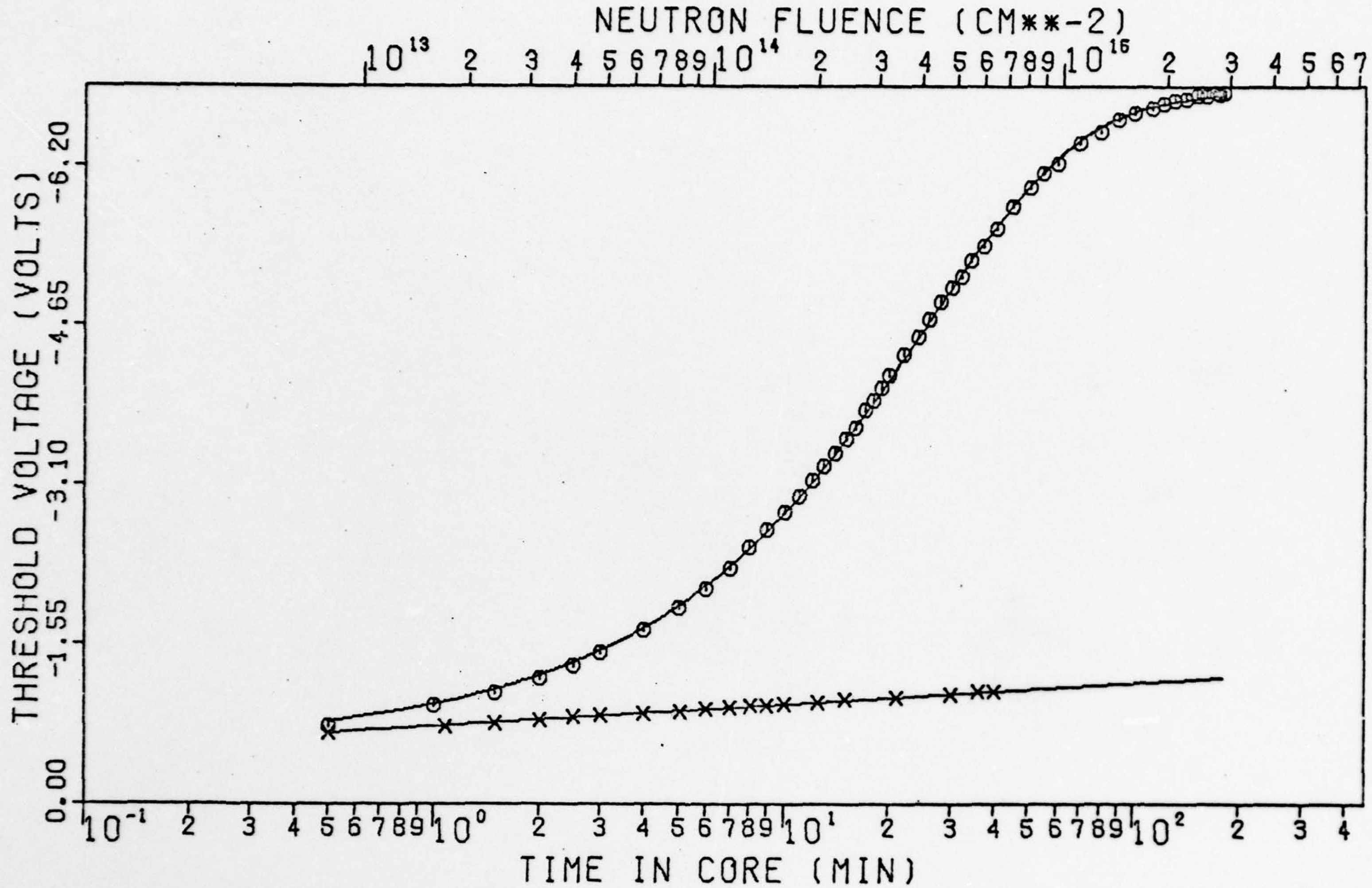

Fig. 10. Threshold Voltage Versus Time in Core and Threshold Voltage Versus Time, Device #16

had leveled off near ΔV_{TMAX}. One transistor was run twice, the other was run four times over two consecutive days. Fig. 11 shows the results of two consecutive runs with Device #4. A small parallel offset is evident in the data points. Equation (20) was fitted to the data from these tests and the results with their standard deviations are shown in Table II.

Table II

Repeatability of ΔV_T for MNOS in Reactor

Device #	Run #	ΔV_{TMAX} (volts)	B' (min^{-1})
4	1	-5.931 ± 0.015	0.03993 ± 0.00028
4	2	-6.017 ± 0.013	0.04249 ± 0.00026
15	1	-5.606 ± 0.013	0.03942 ± 0.00025
15	2	-5.700 ± 0.010	0.04127 ± 0.00017
(overnight delay)			
15	3	-5.655 ± 0.012	0.03866 ± 0.00021
15	4	-5.697 ± 0.013	0.04382 ± 0.00027

Data for changes in V_T due to time were taken at the start of each day. On the second run of the day, the device shows a decided trend to a higher ΔV_{TMAX} and a larger radiation damage constant B'.

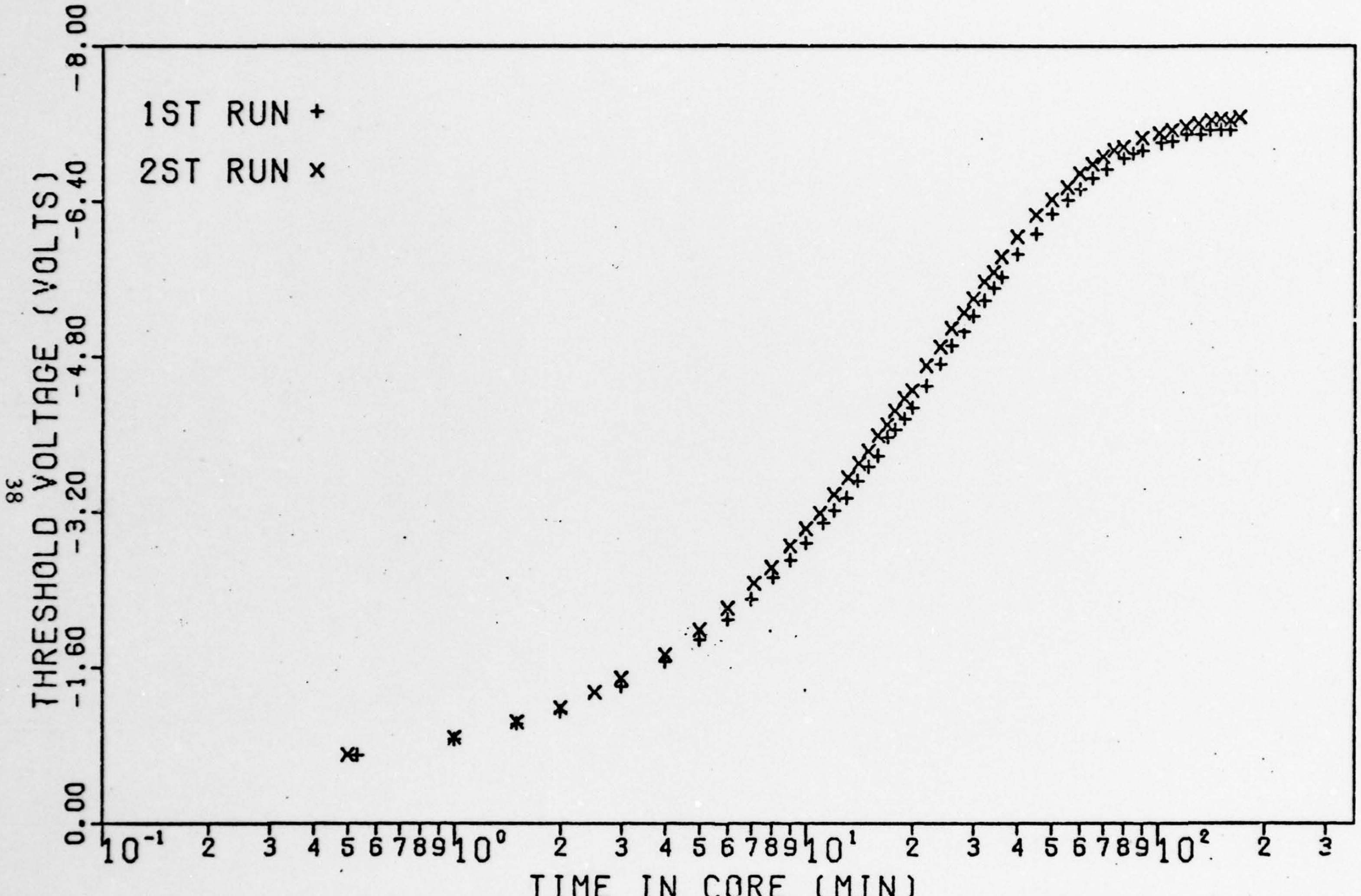

Fig 11. Threshold Voltage Versus Time in Core for Two Runs, Device #4

The next experiment involved testing a cadmium covered transistor. The cadmium was expected to shield the transistor from 85% of the neutrons below 0.475 eV in energy. A series of four runs over two days were made with the cadmium covered device. Table III shows the result of fitting equation (20) to the ΔV_T's for the four runs.

Table III

Repeatability of ΔV_T for a Cd Covered MNOS in Reactor, Device #18

Run #	ΔV_{TMAX} (volts)	B' (min^{-1})
1	-5.441 ± 0.007	0.04370 ± 0.00016
2	-5.500 ± 0.031	0.04306 ± 0.00047
(3 day delay)		
3	-5.435 ± 0.011	0.04190 ± 0.00021
4	-5.456 ± 0.013	0.04326 ± 0.00020

Table III shows the same trend as in Table II, with the second run of the day showing an increase in ΔV_{TMAX} and B'. However, the increase is within 3 standard deviations for three out of the four changes. Fig. 12 shows the changes in V_T due to radiation and time for two runs of the cadmium covered MNOS transistor.

Neutron Damage. The first noticeable change in the transistors

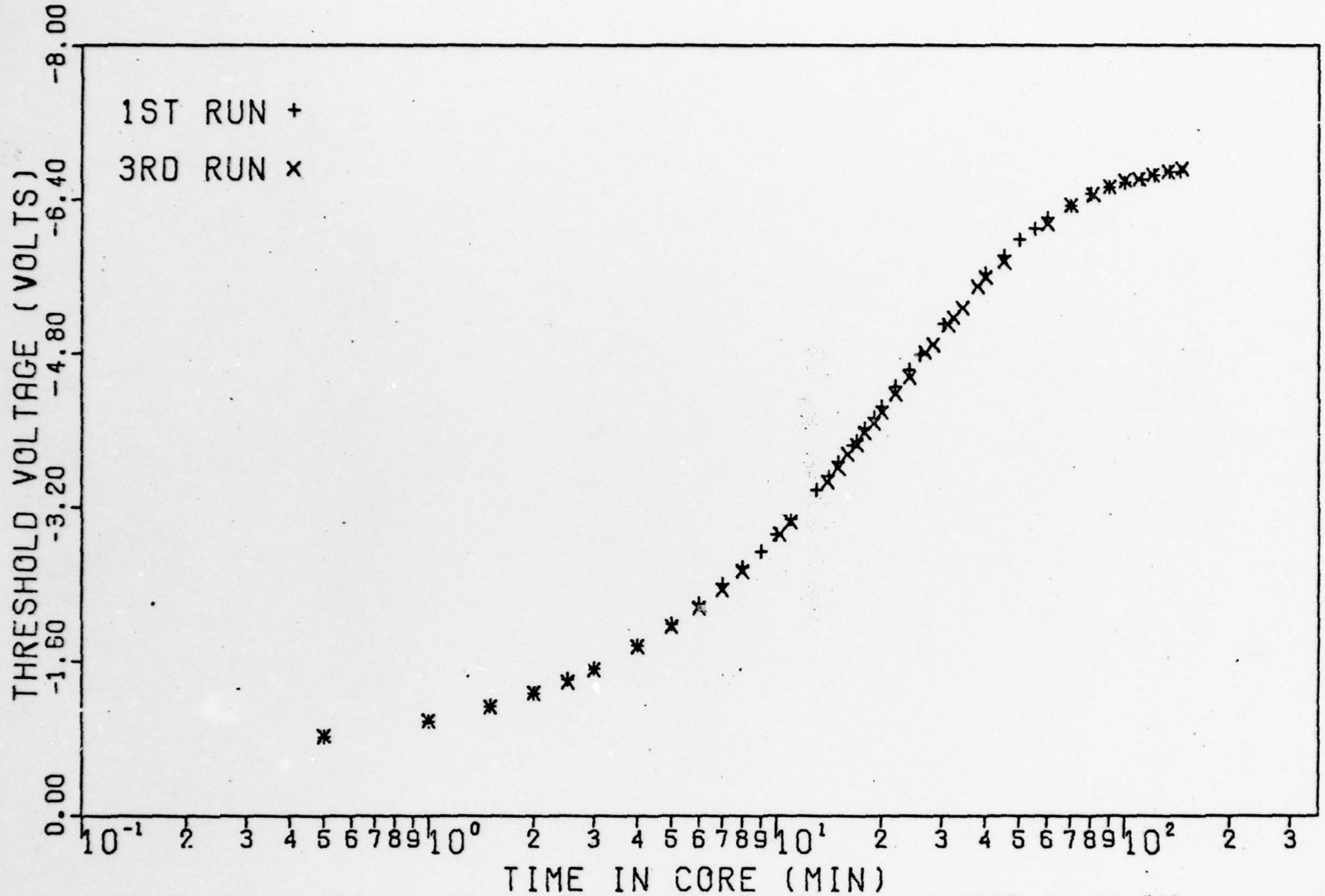

Fig. 12. Threshold Voltage Versus Time in Core for Cd Covered MNOS, Device #18

due to exposure to neutrons, was an increased amount of write pulses required to put the devices into the saturated high conduction state. Typically, the number of required write pulses rose from four or five to as many as twelve or thirteen.

Another aspect of damage was the increase of the magnitude of the threshold voltage of saturation and the slope of the change of V_T with time line. The cadmium covered transistor showed the least amount of total change in V_T at saturation and the slope, 12% and 6% respectively. The second device in Table II showed changes of 28% and 17% respectively. The transistors did show a tendency to recover after two or three days annealing at room temperature, changing by two or three percent.

Two of the transistors were retested in the AFIT gamma facility after being exposed to neutrons from the reactor. Table IV lists the parameters to the equation (20) fit for both gamma irradiations of the two devices.

Table IV

Neutron Damage to MNOS Used as Gamma Dosimeters

Device #	Before/ After	ΔV_{TMAX} (volts)	B ($rads^{-1}$)	Neutron Fluence (cm^{-2})
16	B	4.888 ± 0.036	$1.087 \pm 0.013 \times 10^{-6}$	
16	A	4.791 ± 0.014	$1.083 \pm 0.009 \times 10^{-6}$	3.05×10^{15}
15	B	4.786 ± 0.032	$1.104 \pm 0.012 \times 10^{-6}$	
15	A	4.637 ± 0.024	$1.067 \pm 0.013 \times 10^{-6}$	1.91×10^{16}

Device #16 showed virtually no damage in the ΔV_{TMAX} or B. The before and after results were within three standard deviations. Device #15 showed slightly greater damage a change of 3.2% and 1.7%, respectively.

V. Discussion and Recommendations

This chapter presents a discussion of experiments and their results. It also recommends areas where further studies of neutron effects on MNOS transistors are needed before a neutron dosimeter can be developed using a MNOS device.

Discussion

The results of this study showed two things. They confirmed earlier work by Fraass by showing that a MNOS transistor could be used as the detector in a gamma ray dosimeter. The second thing was that a MNOS transistor could operate in the combined flux of neutrons and gamma rays in a nuclear reactor.

The changes in the threshold voltage (ΔV_T) of the transistor due to gamma radiation can be expressed in the following equation

$$\Delta V_T = \Delta V_{TMAX} \left[1 - \exp(-BR)\right] \tag{21}$$

where ΔV_{TMAX} is the maximum threshold voltage shift given an infinite absorbed dose, R is the absorbed dose in rads, and B is the radiation absorption constant in rads^{-1}. By modifying equation (21), so that the exponent became $B'T$ where $B' = B\dot{R}$, equation (21) described the change in the threshold voltage due to time spent in the

reactor radiation.

The experiments with the cadmium covered device showed the MNOS device could give reproducible results with a 2% precision. The uncovered devices showed a slightly larger parallel increase in V_T when run multiple times.

The ability of the MNOS transistor to function as a gamma ray dosimeter seemed to be unaffected by a neutron fluence up to 1.9 X 10^{16} cm^{-2}. Calibration of the gamma dosimeter seemed to be unaffected by a neutron fluence of 3.1 X 10^{15} cm^{-2}.

Suspected neutron damage includes changes in the nitride layer requiring more write voltage pulses to be applied to reach the saturated high conduction state and causing an increase in the leakage of trapped charges out of the nitride.

The question left unanswered by the results was the reason behind the anomolous 15-20% increase in ΔV_{TMAX} over gamma dose calibrations. One possible cause might lie in the higher energy per unit volume deposited by neutrons than by gamma rays. The local ionization in the nitride layer would increase due to the neutrons. This would increase the ohmic conduction current in the nitride layer. What effect this would have on the maximum threshold voltage shift is unknown.

Recommendations

Before using the MNOS transistor in a neutron dosimeter more studies need to be done on the effects of neutron radiation. This study should be carried out at a neutron facility that produces a high fluence of neutrons with minimal amounts of gamma rays in order to separate the effects of the two. Information is also needed on the effects caused by neutrons with different energy. These studies should be able to explain the anomolous increase in ΔV_{TMAX}.

Further study is recommended on determining what fluence of neutrons will damage the transistor so that it operates beyond its original gamma ray dosimetry calibration.

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Vita

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Metal-Nitride-Oxide-Semiconductor (MNOS) transistors were evaluated as radiation dosimeters in the neutron-gamma radiation field of a nuclear reactor as compared to their behavior when exposed to gamma rays from a calibrated ^{60}Co source at 40.3 krads (Si) per hour.

Their response to gamma rays confirmed the results of a previous study which showed that the change in the threshold voltage for conduction, Delta V sub T

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Delta V sub TMAX

ΔV_T, followed a relation $\Delta V_T = \Delta V_{TMAX} \cdot (1 - e^{-BR})$ where R is the total absorbed dose and ΔV_{TMAX} is the maximum change in threshold voltage for an infinite radiation dose. For gamma irradiation, ΔV_{TMAX} approaches ≈5 volts at an exposure of ≈4 Mrads (Si). Response to reactor radiation follows the same relation except for an anomalous increase of ≈20% in ΔV_{TMAX}. When shielded with cadmium, ΔV_T upon repeated irradiation is reproducible within 2% for four runs. When unshielded, a small parallel offset in ΔV_T results.

about

about Delta V sub T

The devices have survived neutron fluences of 1.9 X 10^{16} cm^{-2}. After irradiation in the reactor, the responses of two devices to gamma rays were within 5% of pre-irradiation values.

A simple schematic is given for the testing circuit along with procedures to follow to determine gamma ray doses from the MNOS device.